NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

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AN INVESTIGATION OF AIRCRAFT HEATERS

II - PROPERTIES OF GASES

By Myron Tribus and L. M. K. Boelter
University of California

WASHINGTON

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AN INVESTIGATION OF AIRCRAFT HEATERS

II - PROPERTIES OF GASES

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A list of properties of the following pure gases and air which are pertinent to airplane heat transfer calculations has been compiled from the literature for the temperature range encountered in airplane operation:

Air

Hydrogen

Nitrogen

Oxygen

Carbon dioxide

Carbon monoxide

The properties of exhaust gases of various compositions are not available to the authors, but it is suggested that the properties of air be utilized for exhaust gas calculations until more exact data are made available.

The reader must be cautioned that when utilizing generalized heat transfer equations or their graphical counterpart, the physical properties which were employed by the experimenter must be substituted into the generalized expressions in order that the proper magnitude of the unit conductance will result.

SYMBOLS

C_p unit heat capacity at constant pressure, Btu/lb °F

C_v unit heat capacity at constant volume, Btu/lb °F

f ratio of $\frac{k}{\theta_v \mu} = 3600\ g\ \epsilon$, ft/hr sec

g gravitational force per unit mass, $\dfrac{\text{lb}}{\left(\dfrac{\text{lb sec}^2}{\text{ft}}\right)}$

k thermal conductivity, $\dfrac{\text{Btu}}{\text{hr ft}^2\left(\dfrac{^\circ\text{F}}{\text{ft}}\right)}$

T temperature (abs.), $^\circ$R

μ absolute viscosity, lb sec/ft^2

Pr Prandtl modulus, $\dfrac{\mu\, c_p(3600\ g)}{k}$

ϵ ratio, $\dfrac{k}{\mu\, c_v(3600\ g)}$

The data presented herein represent the work of many experimenters.

The values for specific heats were taken directly from Heck (reference 1) and converted to the engineering system of units. The original work of Heck extends from 140° to 4940° F and is probably the best obtainable. It is based upon spectroscopic measurements.

Williams (reference 2) has shown that, if Sutherland's equations (reference 3) for the viscosity of a gas holds, a plot of $T^{3/2}/\mu$ against T should give a straight line. When such plots were constructed, it was found that all the gases except hydrogen yielded straight lines. For hydrogen it was found that the ratio $T^{2/3}/\mu$ was constant within the accuracy of the experimental results. Using the equation $\mu = C\, T^{2/3}$ for hydrogen, and

$\mu = C_1 \dfrac{T^{3/2}}{T + C_2}$ for the other gases, excellent agreement was

obtained between the calculated values and the measured values of the viscosity. In the case of carbon dioxide and oxygen, the deviations from experimental values were nearly all less than 1 percent.

In contrast with the data for unit heat capacity and

viscosity, there is a paucity of accurate data on thermal conductivities of gases. Laby and Nelson (reference 4) found among 19 observers an average deviation of 7 percent in the values reported for the thermal conductivity of air at 32° F. The data for other gases are less plentiful. Only three measurements of the thermal conductivity of carbon monoxide were found, all near 32° F.

In modern engineering practice, however, it is often desired to know thermal conductivites at temperatures other than 32° F. Rather than make an outright guess, the following theoretical relationship was utilized (reference 5):

$$k = (3600\ g\,\epsilon)\ \mu\ C_v = f\ \mu\ C_v$$

From the measured values of k, μ, and C_v, values of f were calculated and plotted against temperature. If a definite variation in f as a function of T could be found, such a variation was used as a basis for predicting k at temperatures at which it has not been measured, using the measured values of μ and C_v. Such a method is subject to many errors, obviously, but it was the best that could be devised. The results are unsatisfactory, but until a better scheme is devised or more data are presented, they will have to serve as the basis for high temperature calculations. The tabulated values of thermal conductivities are based on the derived equations.

The probable errors are based on the average deviation of experimental results from the "best curve." In such a case as k for CO, judgment based on three measured values at 32° F can hardly be considered more than a guess when applied to values at 1000° F.

These properties are all independent of pressure in the range two atmospheres down to 5 millimeters of mercury. Shown below are the temperature ranges for which experimental data were available, and the temperatures for which certain properties were extrapolated as discussed above.

Grateful acknowledgment is due Messrs. E. B. Weinberg and H. F. Brockschmidt for their help in preparing the report.

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TEMPERATURE-RANGE OF EXPERIMENTAL DATA

Gas	Range in which data are available (deg F)	Range in which curves were extrapolated (deg F)
Air		
Heat capacity (C_v)	(Calculated from O_2 and N_2 values)	
Viscosity	-109 to 1600	———
Thermal conductivity	-109 to 590	590 to 1600
Hydrogen		
Heat capacity (C_v)	-100 to 4940	———
Viscosity	-113 to 1517	———
Thermal conductivity	-113 to 608	608 to 1600
Nitrogen		
Heat capacity (C_v)	-100 to 4940	———
Viscosity	-106 to 1516	———
Thermal conductivity	-108 to 212	212 to 1600
Oxygen		
Heat capacity (C_v)	-100 to 4940	———
Viscosity	59 to 1524	-100 to 59
Thermal conductivity	-109 to 212	212 to 1600
Carbon dioxide		
Heat capacity (C_v)	-100 to 4940	———
Viscosity	30 to 1600	-100 to 30
Thermal conductivity	-109 to 602	602 to 1600
Carbon monoxide		
Heat capacity (C_v)	-100 to 4940	———
Viscosity	-109 to 530	530 to 1600
Thermal conductivity	32 to 51	-200 to 32 51 to 1600

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TABLE I.– AIR

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ft}^2 \text{ hr } \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	0.2393	0.280	1.04	0.743
0	.2398	.343	1.30	.731
100	.2403	.398	1.57	.706
200	.2412	.449	1.82	.690
300	.2427	.498	2.05	.682
400	.2449	.542	2.28	.677
500	.2476	.587	2.50	.672
600	.2505	.630	2.72	.668
700	.2534	.663	2.93	.666
800	.2566	.699	3.14	.663
900	.2598	.732	3.34	.660
1000	.2630	.767	3.55	.658
1100	.2660	.800	3.76	.655
1200	.2690	.832	3.99	.652
1300	.2715	.864	4.19	.650
1400	.2740	.896	4.40	.648
1500	.2766	.928	4.61	.646
1600	.2789	.960	4.84	.643

TABLE II.- HYDROGEN

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ft}^2\ \text{hr}\ \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	3.393	0.143	7.5	0.870
0	3.413	.169	9.5	.707
100	3.432	.192	11.4	.671
200	3.449	.215	13.1	.654
300	3.359	.235	14.7	.640
400	3.466	.254	15.9	.640
500	3.472	.275	16.9	.654
600	3.476	.294	17.6	.676
700	3.483	.313	18.4	.688
800	3.490	.331	19.4	.687
900	3.501	.347	20.5	.686
1000	3.514	.364	21.6	.685
1100	3.531	.381	22.8	.684
1200	3.551	.397	23.9	.683
1300	3.572	.413	25.2	.681
1400	3.596	.428	26.1	.679
1500	3.621	.443	27.4	.677
1600	3.646	.458	28.7	.675

TABLE III.- NITROGEN

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ft}^2 \text{ hr } \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	0.2478	0.2675	1.03	0.711
0	.2478	.3275	1.32	.711
100	.2484	.3800	1.54	.709
200	.2490	.4285	1.74	.708
300	.2500	.4750	1.94	.707
400	.2515	.5160	2.12	.706
500	.2538	.5560	2.32	.704
600	.2564	.5950	2.52	.701
700	.2592	.6310	2.72	.698
800	.2623	.666	2.91	.695
900	.2655	.700	3.10	.690
1000	.2689	.731	3.30	.688
1100	.2721	.762	3.50	.687
1200	.2751	.792	3.70	.683
1300	.2780	.820	3.88	.681
1400	.2807	.845	4.04	.679
1500	.2835	.871	4.23	.677
1600	.2860	.895	4.40	.674

TABLE IV. - OXYGEN

t (deg F)	C_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ft}^2 \text{ hr } \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-200		0.226		
-100	0.2180	.3051	1.06	0.726
0	.2185	.3772	1.31	.725
100	.2200	.4410	1.59	.724
200	.2228	.500	1.79	.720
300	.2266	.554	2.03	.715
400	.2305	.607	2.28	.709
500	.2350	.654	2.54	.705
600	.2390	.700	2.77	.703
700	.2429	.743	3.01	.698
800	.2465	.785	3.24	.694
900	.2498	.824	3.47	.692
1000	.2528	.861	3.66	.688
1100	.2553	.897	3.90	.686
1200	.2577	.932	4.09	.684
1300	.2599	.965	4.27	.682
1400	.2618	1.000	4.46	.681
1500	.2635	1.030	4.65	.679
1600	.2651	1.060	4.82	.678

TABLE V.– CARBON DIOXIDE

t (deg F)	c_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ft}^2 \text{ hr } \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	0.1885	0.2121	0.57	0.796
0	.1976	.2721	.76	.779
100	.2075	.3275	1.00	.773
200	.2175	.3795	1.23	.762
300	.2280	.4285	1.47	.754
400	.2385	.4765	1.74	.746
500	.2480	.5200	1.99	.736
600	.2565	.5625	2.24	.734
700	.2640	.6040	2.50	.726
800	.2700	.6420	2.72	.723
900	.2760	.6790	2.96	.721
1000	.2815	.7165	3.19	.719
1100	.2861	.7520	3.42	.717
1200	.2905	.7850	3.64	.715
1300	.2945	.8160	3.84	.713
1400	.2984	.8450	4.06	.711
1500	.3018	.8760	4.25	.708
1600	.3050	.9100	4.46	.708

TABLE VI.– CARBON MONOXIDE

t (deg F)	C_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft²)	$k \times 10^2$ $\left(\text{Btu/ hr ft}^2 \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	0.2480	0.267	1.05	0.716
0	.2482	.331	1.29	.716
100	.2486	.382	1.49	.716
200	.2496	.431	1.69	.716
300	.2512	.475	1.89	.713
400	.2532	.518	2.08	.709
500	.2561	.556	2.27	.708
600	.2592	.593	2.46	.704
700	.2627	.624	2.65	.700
800	.2662	.662	2.85	.698
900	.2696	.694	3.05	.694
1000	.2730	.725	3.22	.690
1100	.2763	.755	3.41	.688
1200	.2793	.784	3.60	.684
1300	.2822	.811	3.78	.682
1400	.2850	.834	3.96	.680
1500	.2878	.865	4.14	.678
1600	.2905	.890	4.30	.676

TABLE VI.- CARBON MONOXIDE

t (deg F)	C_p (Btu/lb °F)	$\mu \times 10^6$ (lb sec/ft^2)	$k \times 10^2$ $\left(\text{Btu/ hr ft}^2 \frac{\text{deg F}}{\text{ft}}\right)$	Pr
-100	0.2480	0.267	1.05	0.716
0	.2482	.331	1.29	.716
100	.2486	.382	1.49	.716
200	.2496	.431	1.69	.716
300	.2512	.475	1.89	.713
400	.2532	.518	2.08	.709
500	.2561	.556	2.27	.708
600	.2592	.593	2.46	.704
700	.2627	.624	2.65	.700
800	.2662	.662	2.85	.698
900	.2696	.694	3.05	.694
1000	.2730	.725	3.22	.690
1100	.2763	.755	3.41	.688
1200	.2793	.784	3.60	.684
1300	.2822	.811	3.78	.682
1400	.2850	.834	3.96	.680
1500	.2878	.865	4.14	.678
1600	.2905	.890	4.30	.676

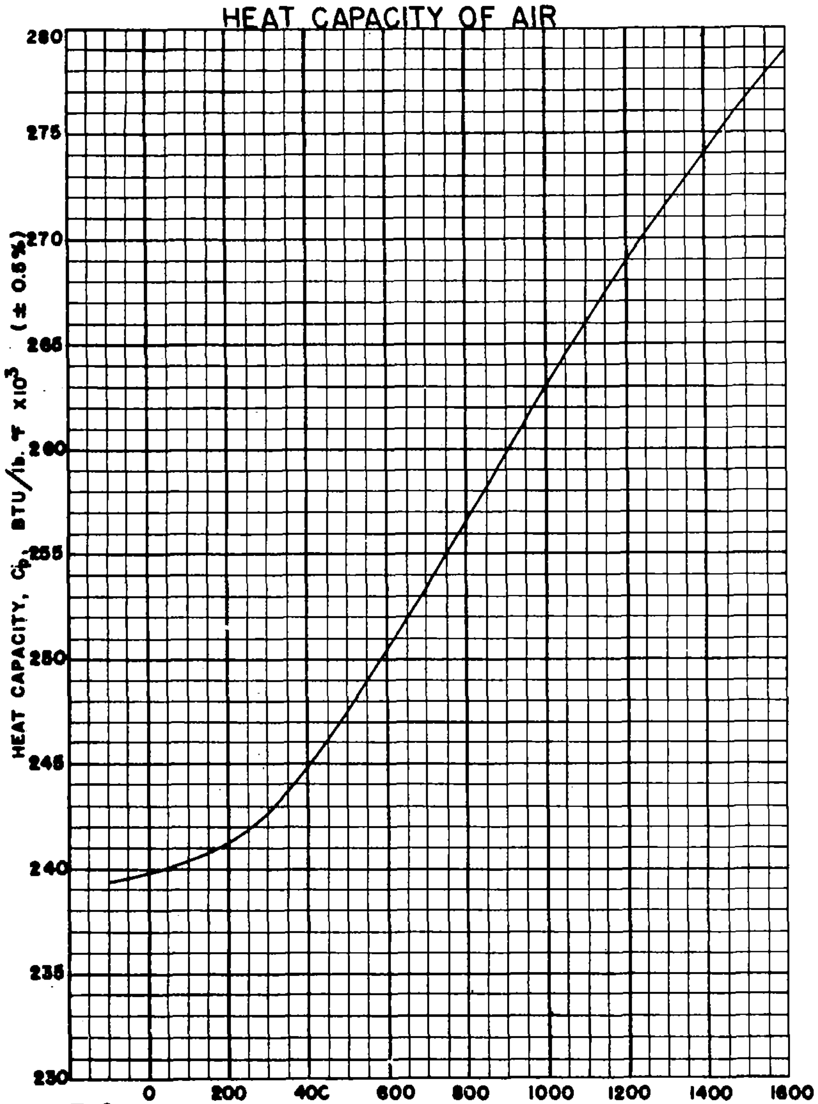
HEAT CAPACITY OF AIR
280
275
270
265
260
255
250
245
240
235
230
HEAT CAPACITY, Cp, BTU/lb. °F x10³ (± 0.5%)
0
200
400
600
800
1000
1200
1400
1600
TEMPERATURE, degrees F

FIG. 1

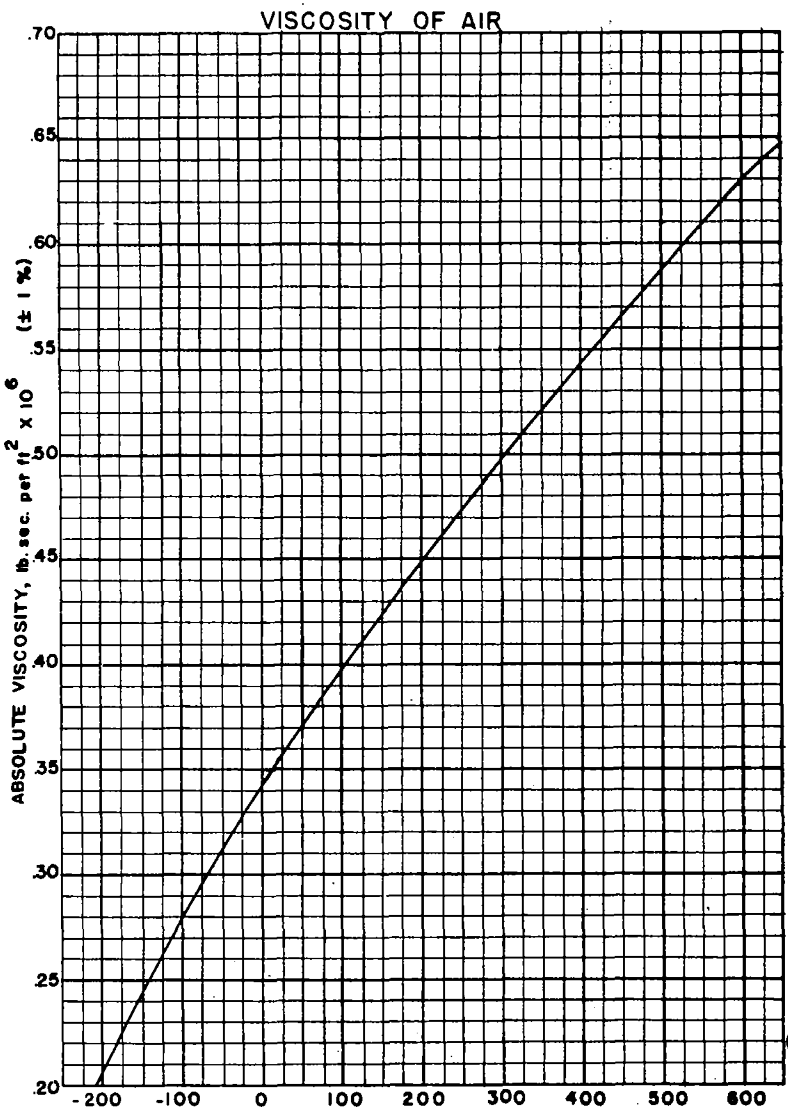
VISCOSITY OF AIR
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
ABSOLUTE VISCOSITY, lb. sec. per ft² x 10⁶ (± 1 %)
-200
-100
0
100
200
300
400
500
600
TEMPERATURE, degrees F

FIG. 2

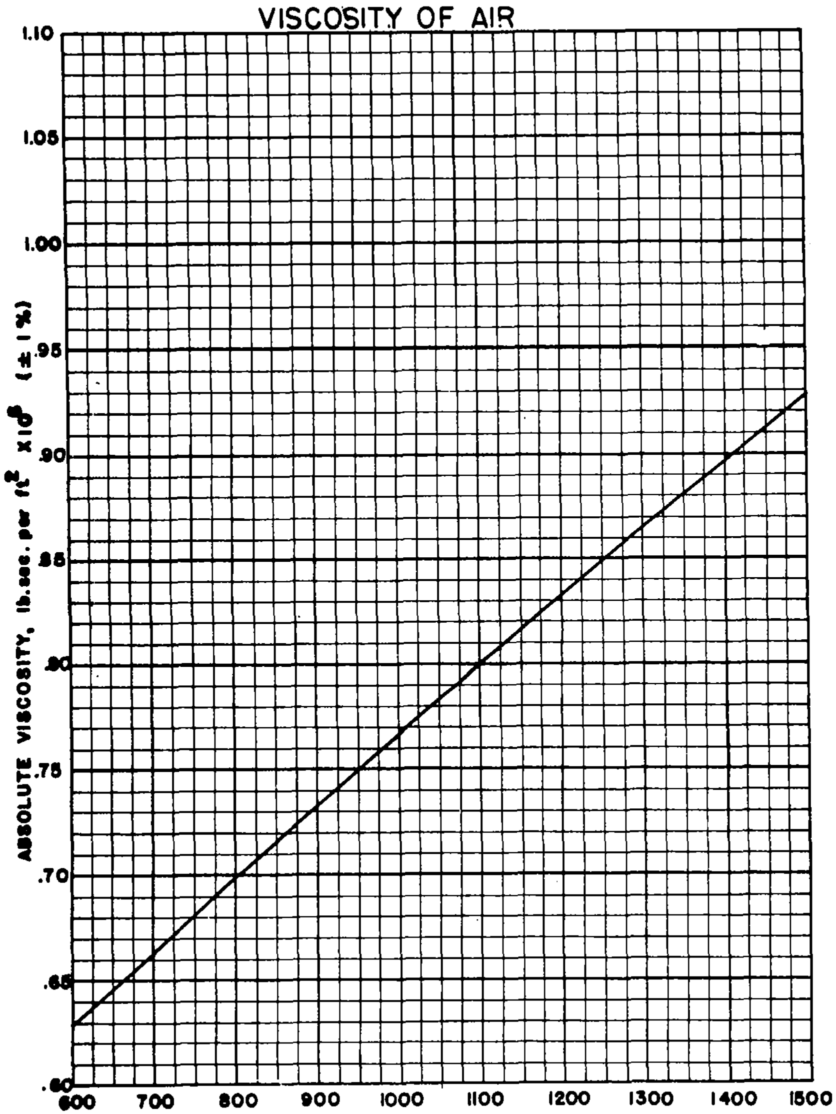
VISCOSITY OF AIR
ABSOLUTE VISCOSITY, lb.sec. per ft.^{2} x 10^6 (± 1 %)
1.10
1.05
1.00
.95
.90
.85
.80
.75
.70
.65
.60
600
700
800
900
1000
1100
1200
1300
1400
1500
TEMPERATURE, degrees F

FIG. 3

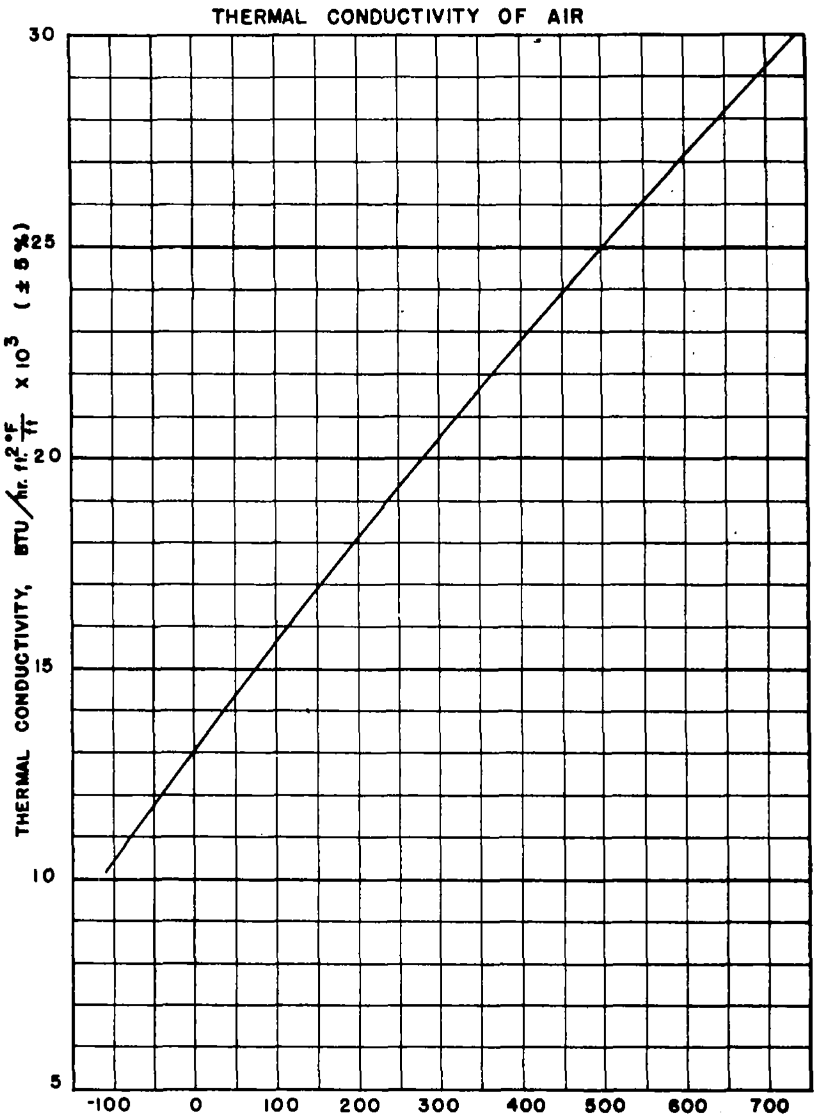
THERMAL CONDUCTIVITY OF AIR
THERMAL CONDUCTIVITY, BTU/hr. ft.^{2} °F/ft x 10^3 (± 5 %)
30
25
20
15
10
5
-100
0
100
200
300
400
500
600
700
TEMPERATURE, degrees F

FIG. 4

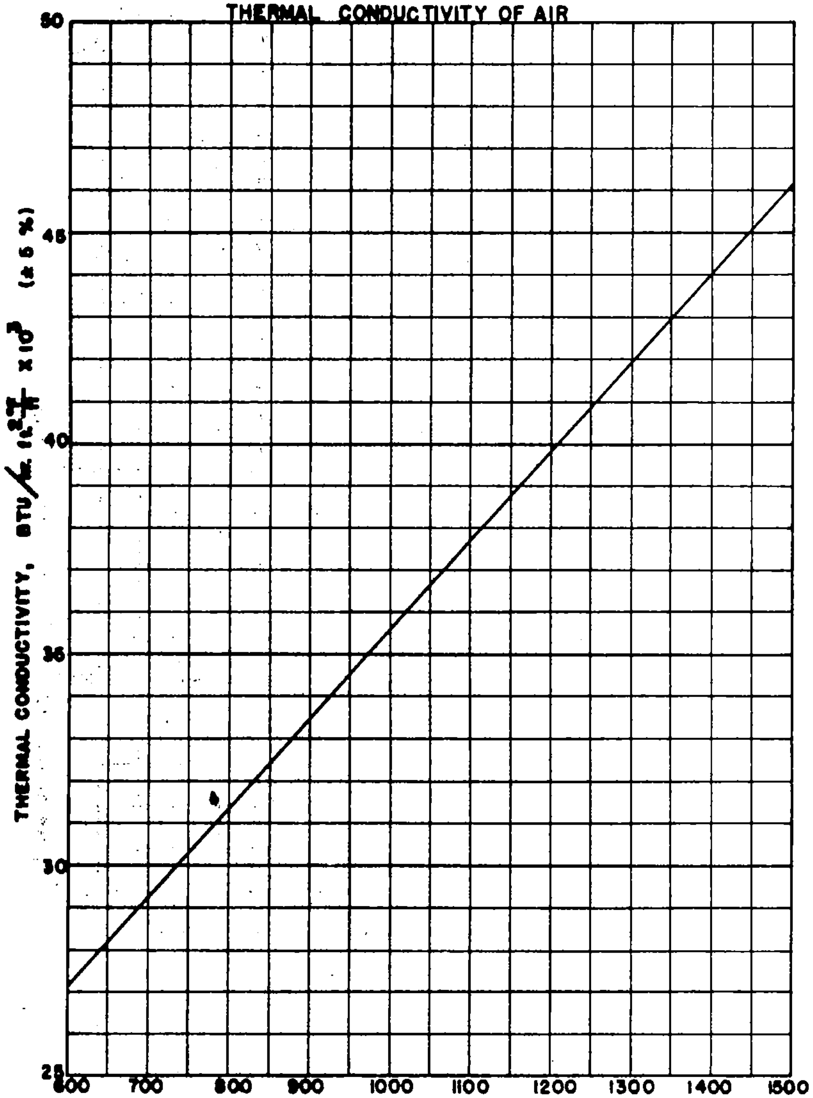
THERMAL CONDUCTIVITY OF AIR
THERMAL CONDUCTIVITY, BTU/ (± 5 %)
50
45
40
35
30
25
600
700
800
900
1000
1100
1200
1300
1400
1500
TEMPERATURE, degrees F

FIG. 5

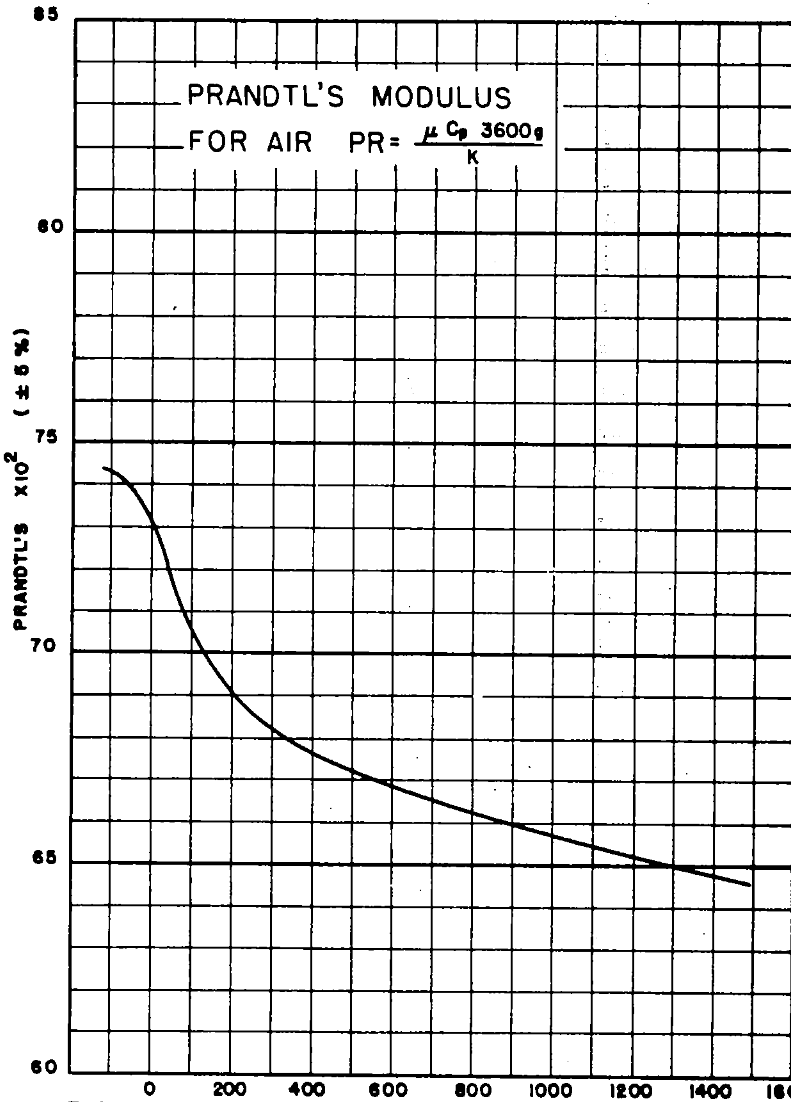
PRANDTL'S MODULUS
FOR AIR PR= $\frac{\mu C_p 3600 g}{K}$
PRANDTL'S X10² (± 5 %)
85
80
75
70
65
60
0
200
400
600
800
1000
1200
1400
1600
TEMPERATURE, degrees F

FIG. 6

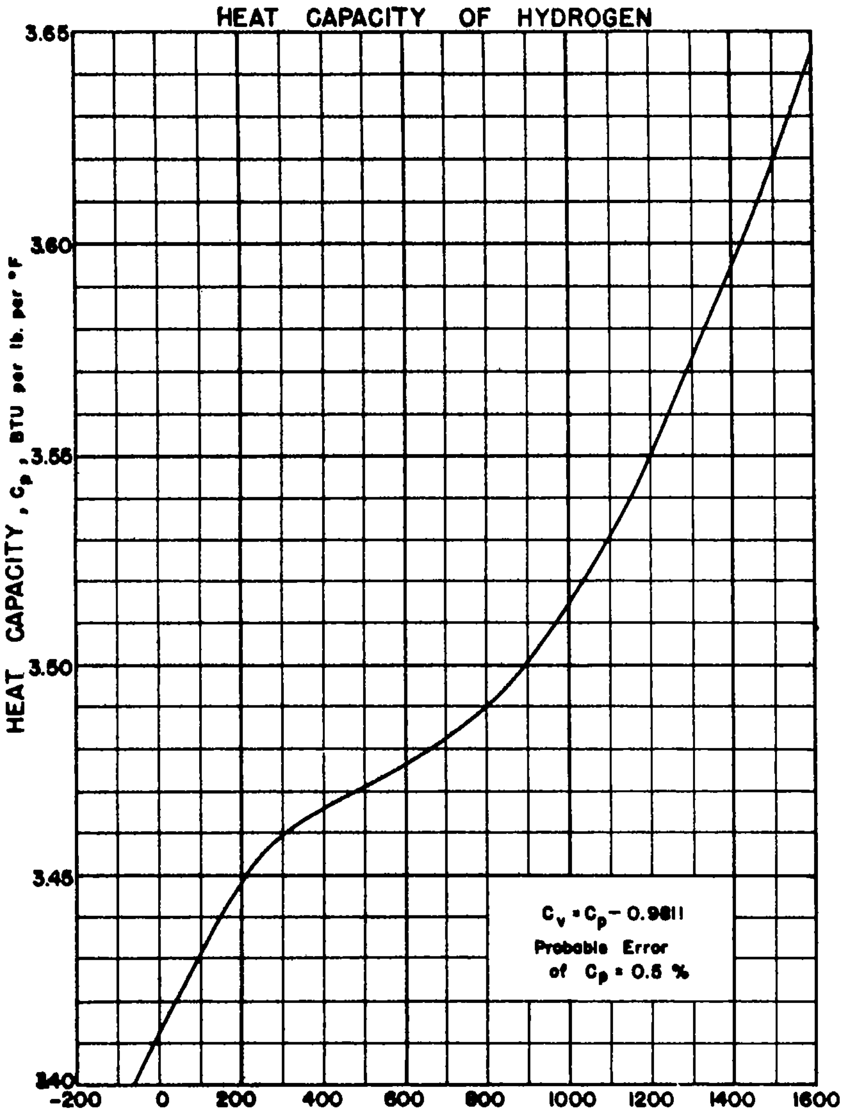

FIG. 7 TEMPERATURE, °F

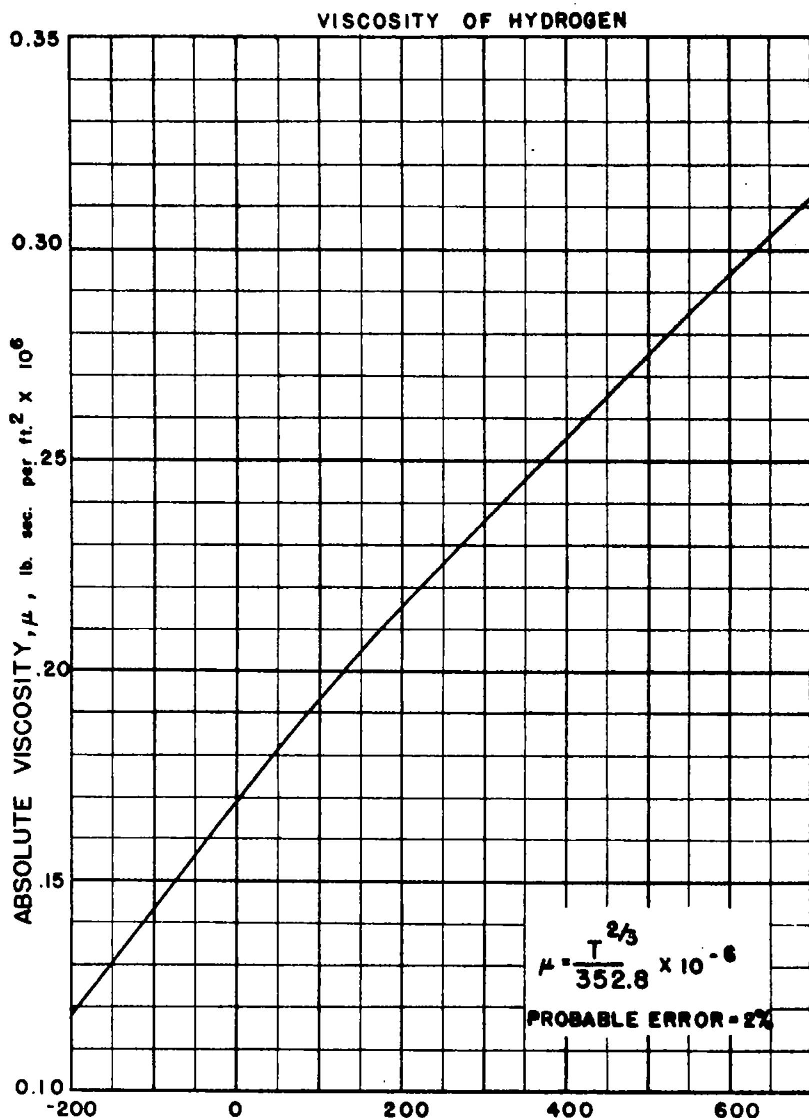

FIG. 8 TEMPERATURE, °F

VISCOSITY OF HYDROGEN

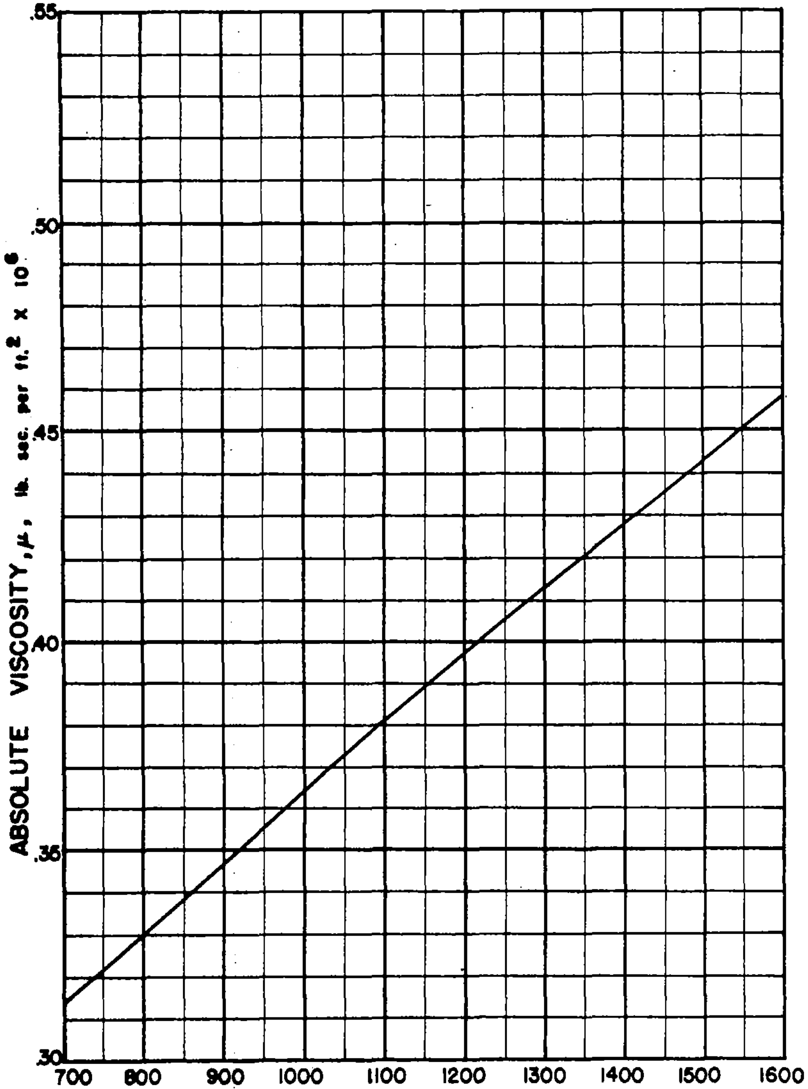

FIG. 9

THERMAL CONDUCTIVITY OF HYDROGEN

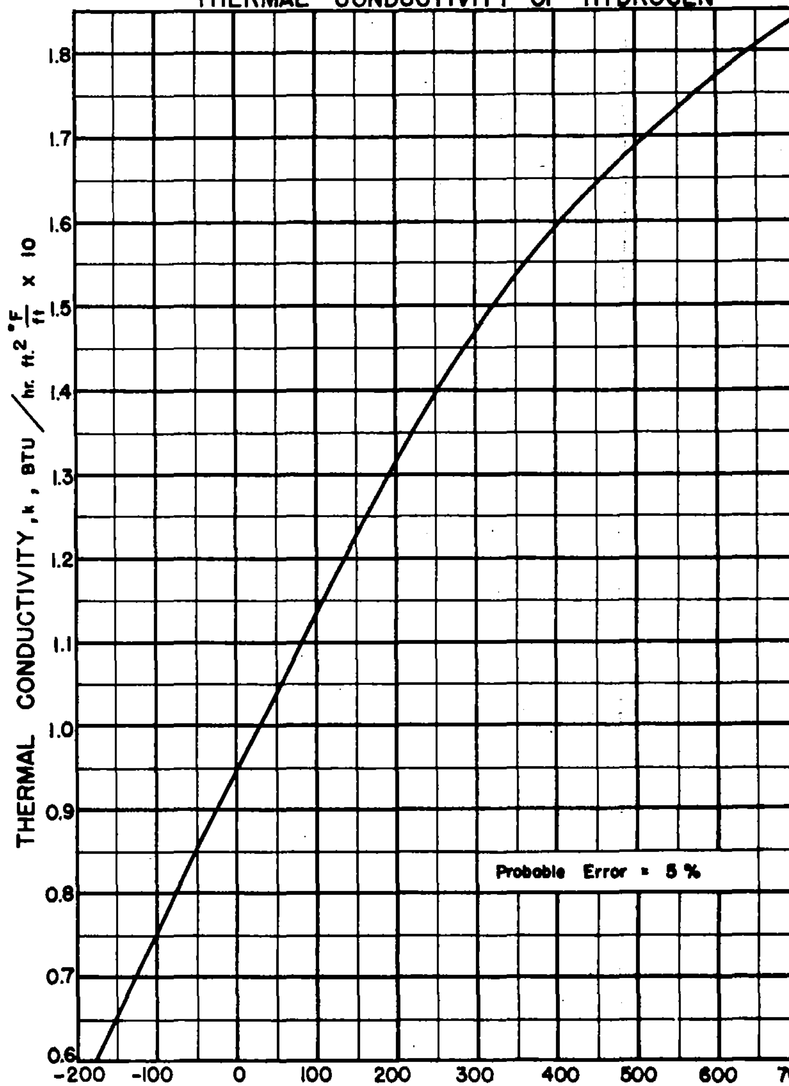

FIG. 10

THERMAL CONDUCTIVITY OF HYDROGEN

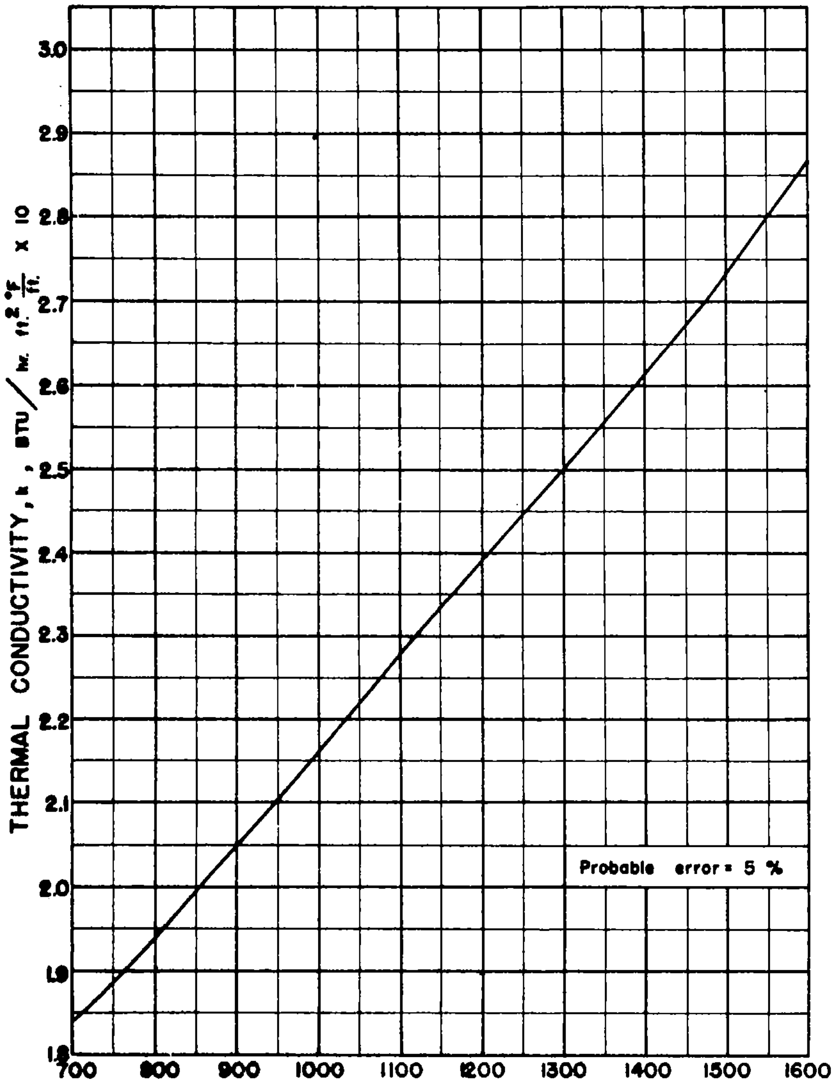

FIG. 11

HEAT CAPACITY OF NITROGEN

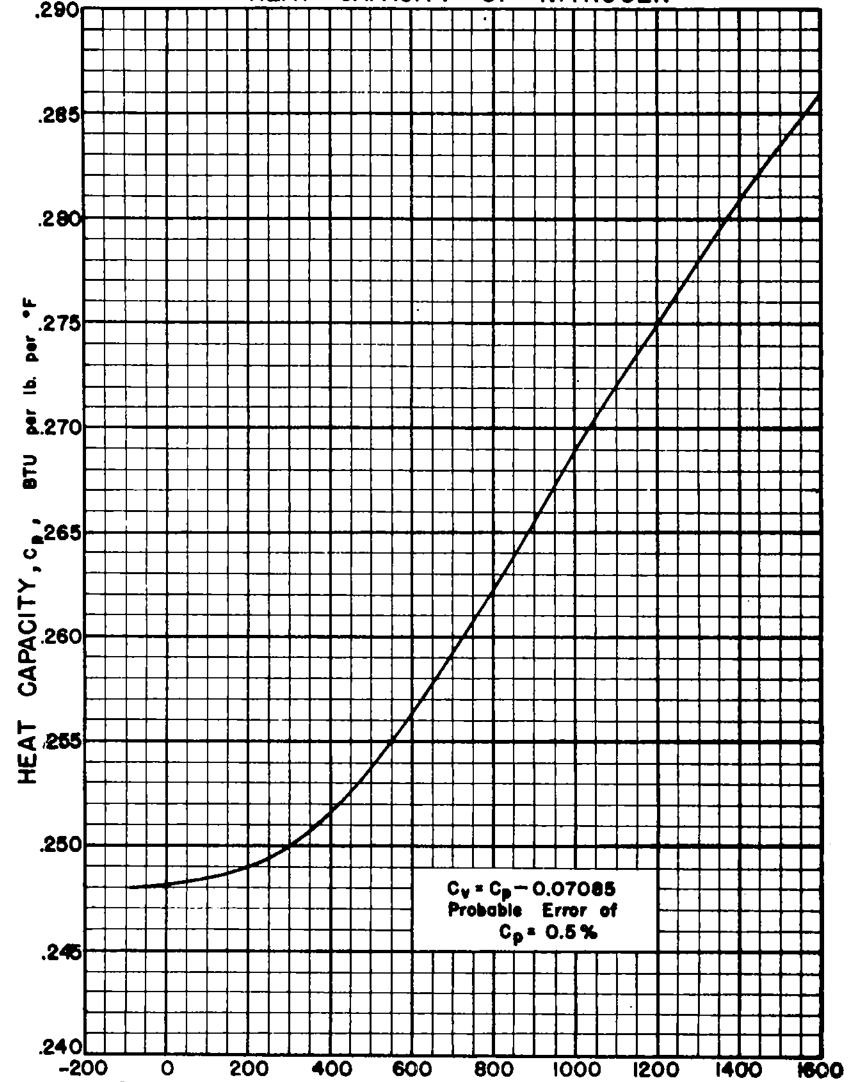

FIG. 12

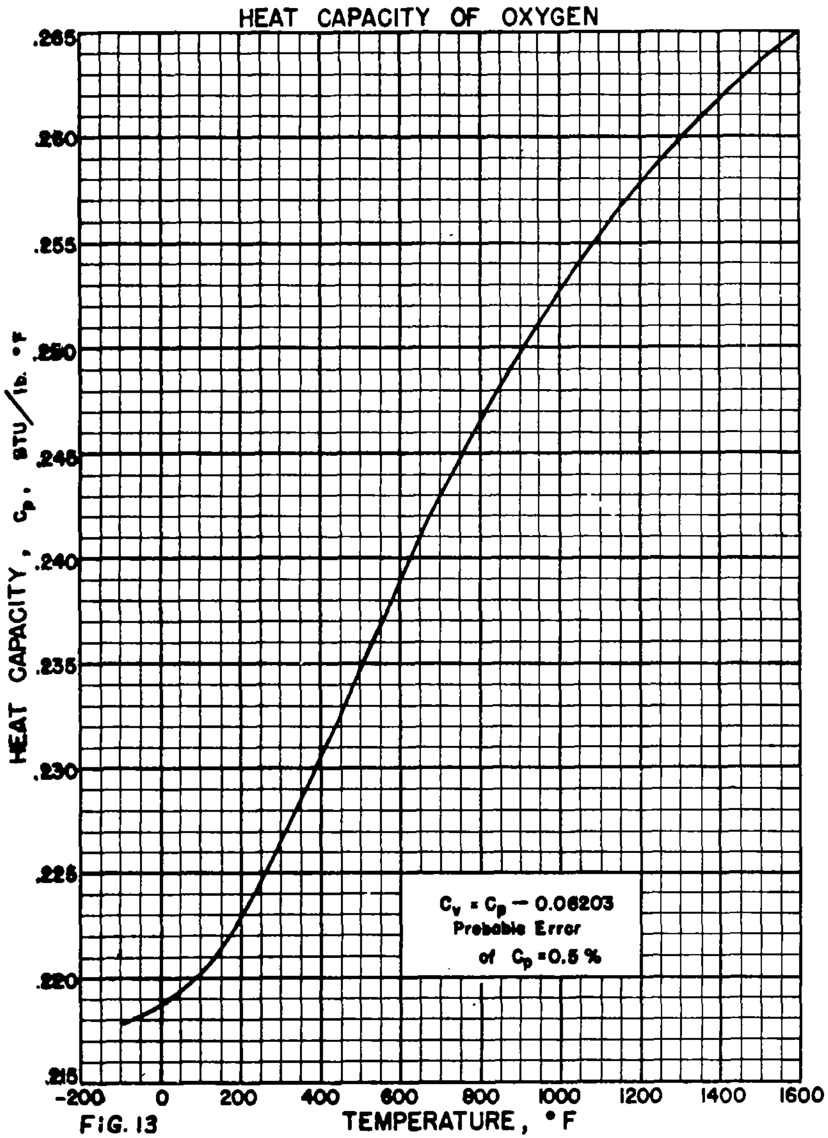
HEAT CAPACITY OF OXYGEN
HEAT CAPACITY, C_p, BTU/lb. °F
TEMPERATURE, °F
.265
.260
.255
.250
.245
.240
.235
.230
.225
.220
.215
-200
0
200
400
600
800
1000
1200
1400
1600
$C_v = C_p - 0.06203$
Probable Error
of C_p = 0.5 %

FIG. 13

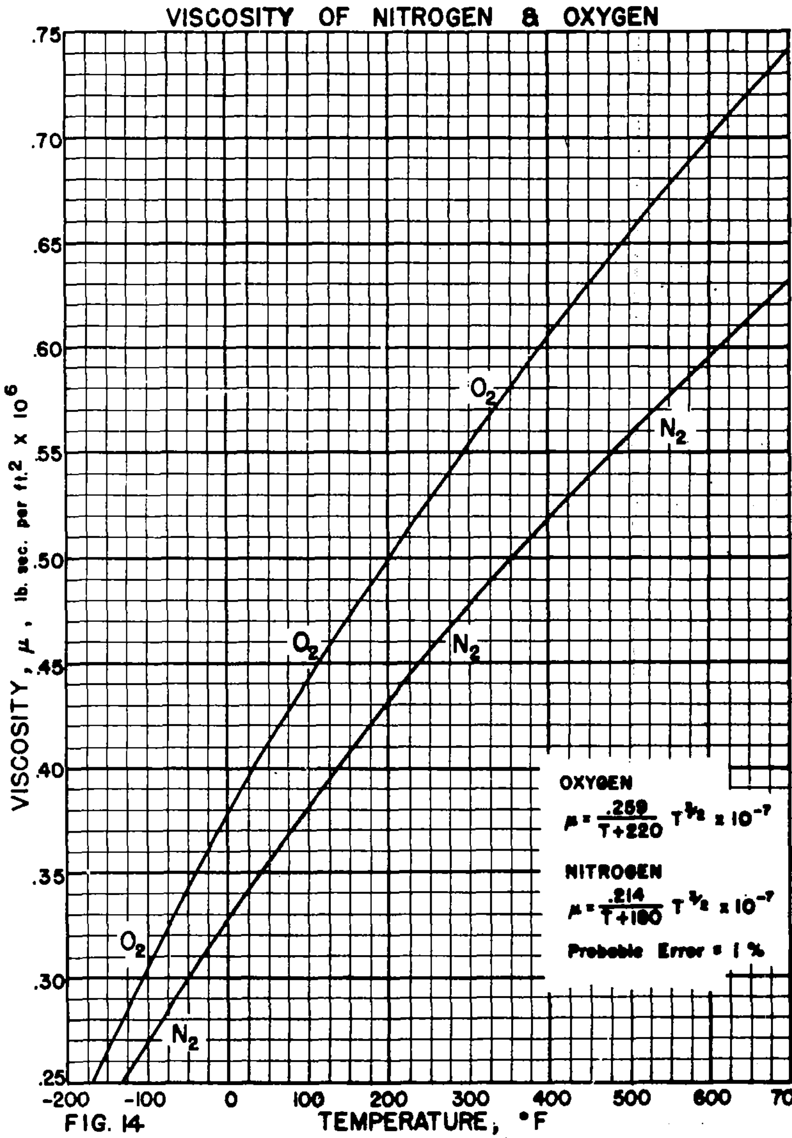
VISCOSITY OF NITROGEN & OXYGEN
VISCOSITY, μ, lb. sec. per ft.^{2} x 10^6
TEMPERATURE, °F
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
-200
-100
0
100
200
300
400
500
600
700
O_2
N_2
OXYGEN
$\mu = \frac{.259}{T+220} T^{3/2} \times 10^{-7}$
NITROGEN
$\mu = \frac{.214}{T+180} T^{3/2} \times 10^{-7}$
Probable Error = 1 %

FIG. 14

VISCOSITY OF NITROGEN & OXYGEN

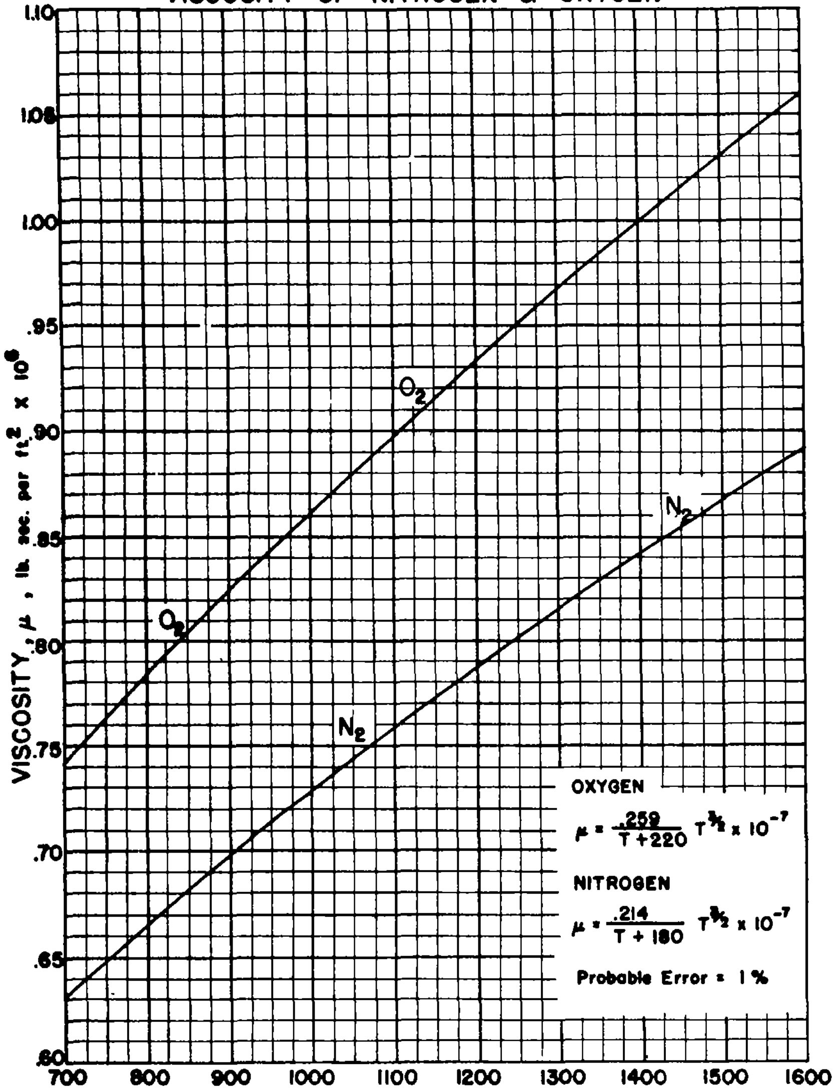

FIG. 15

THERMAL CONDUCTIVITY OF O_2 AND N_2

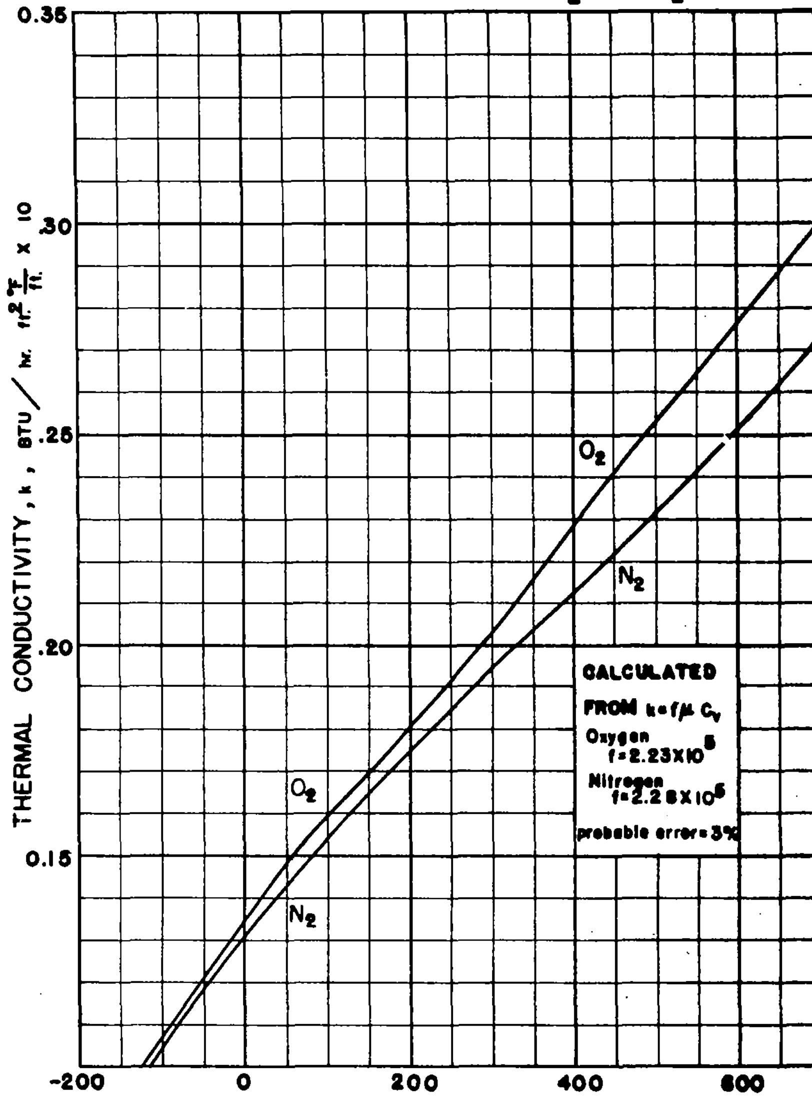

FIG. 16

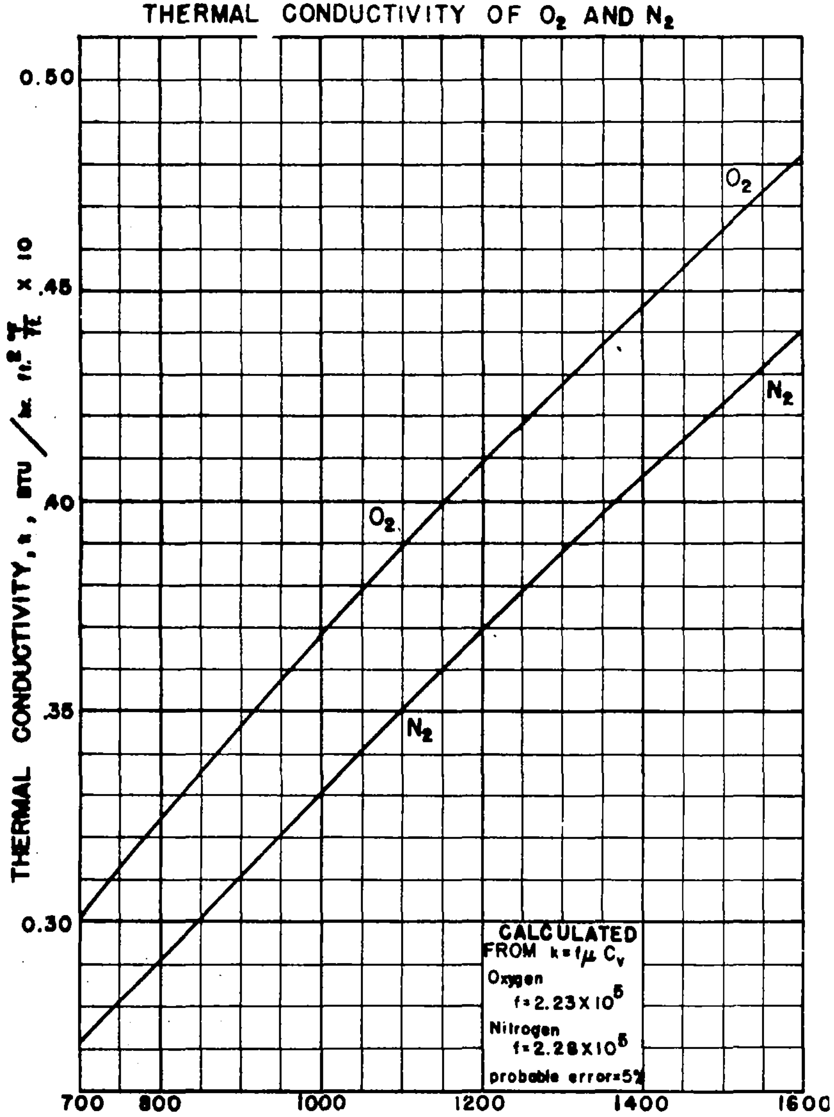

FIG. 17

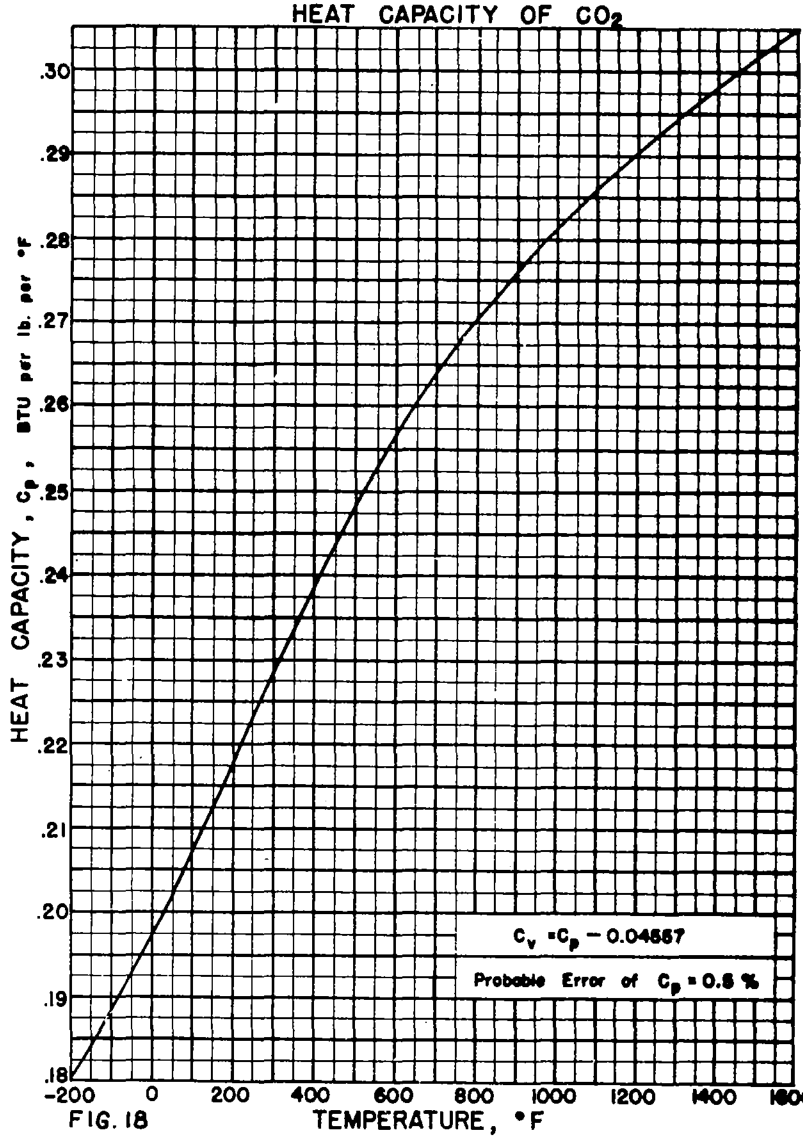

FIG. 18

NACA Figs. 17, 18

VISCOSITY OF CO_2

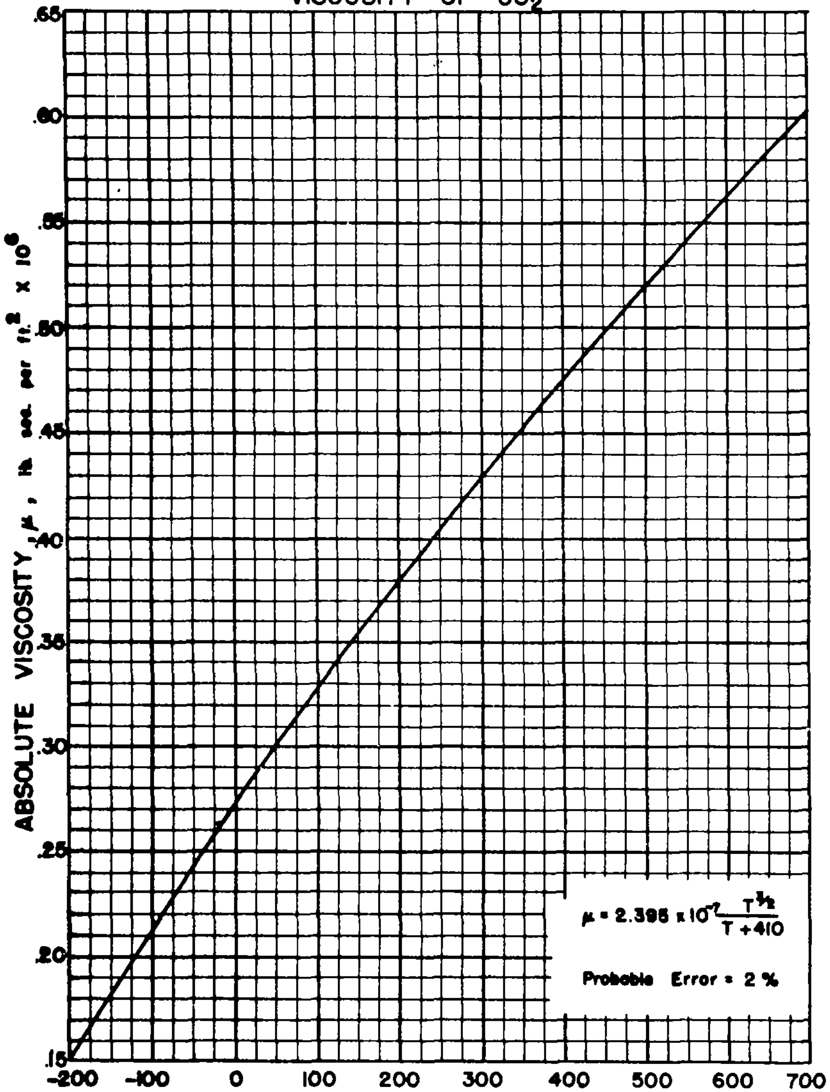

FIG. 19

VISCOSITY OF CO_2

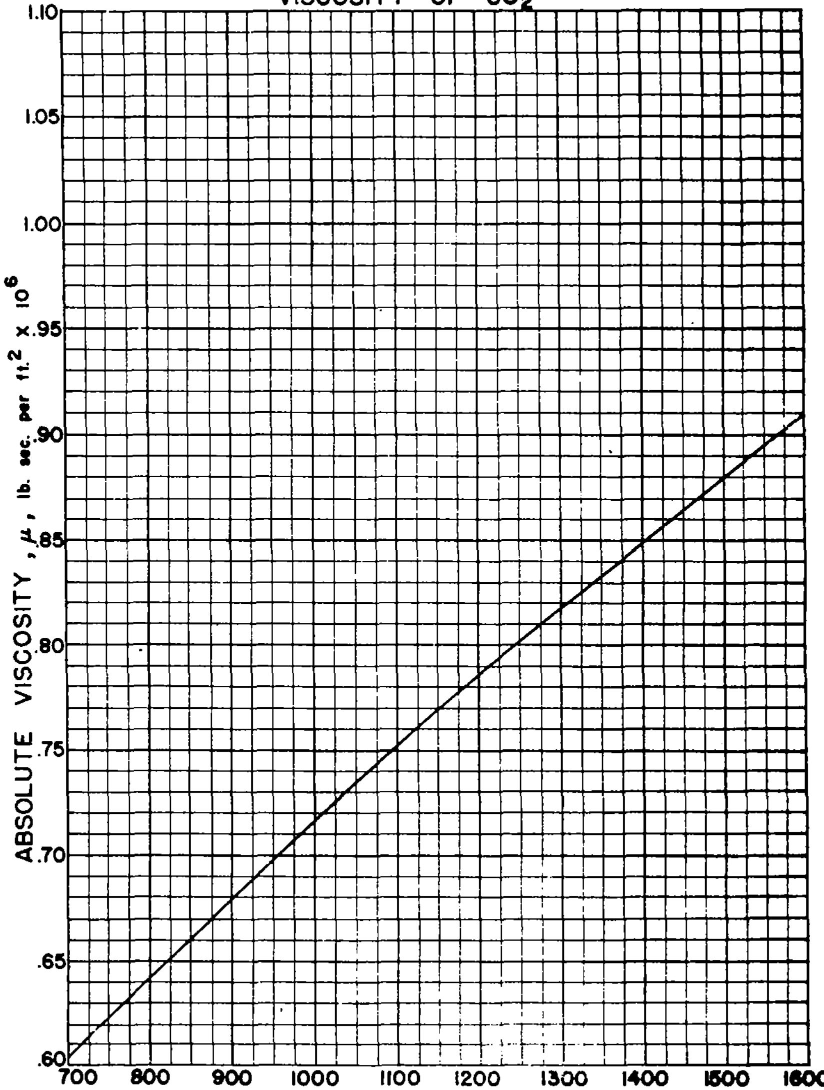

FIG. 20

THERMAL CONDUCTIVITY OF CO_2

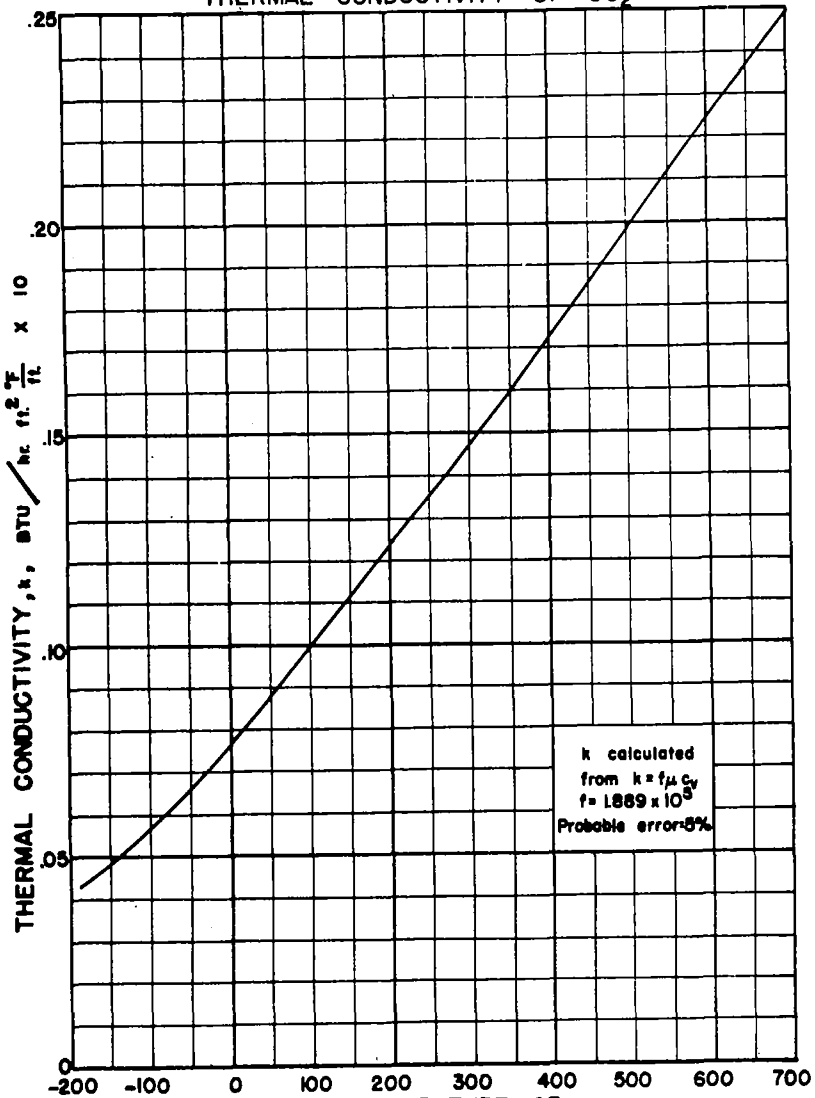

FIG. 21

TEMPERATURE, °F

THERMAL CONDUCTIVITY OF CO_2

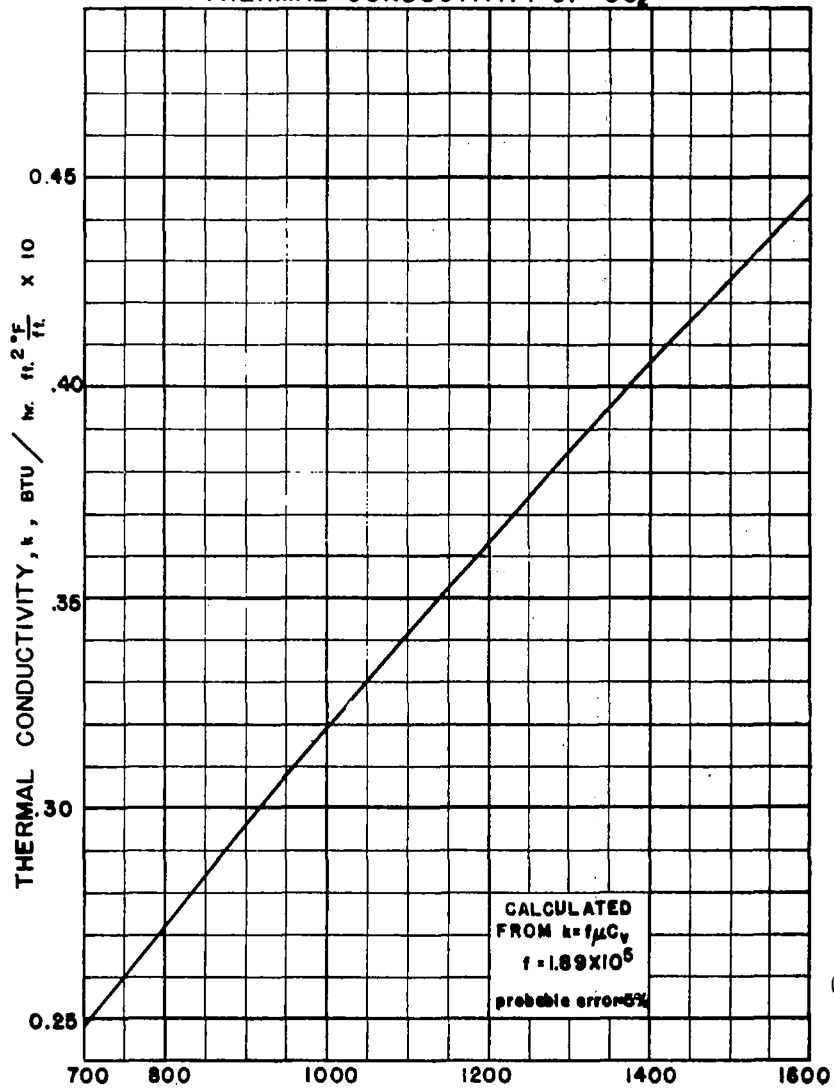

FIG. 22

TEMPERATURE, °F

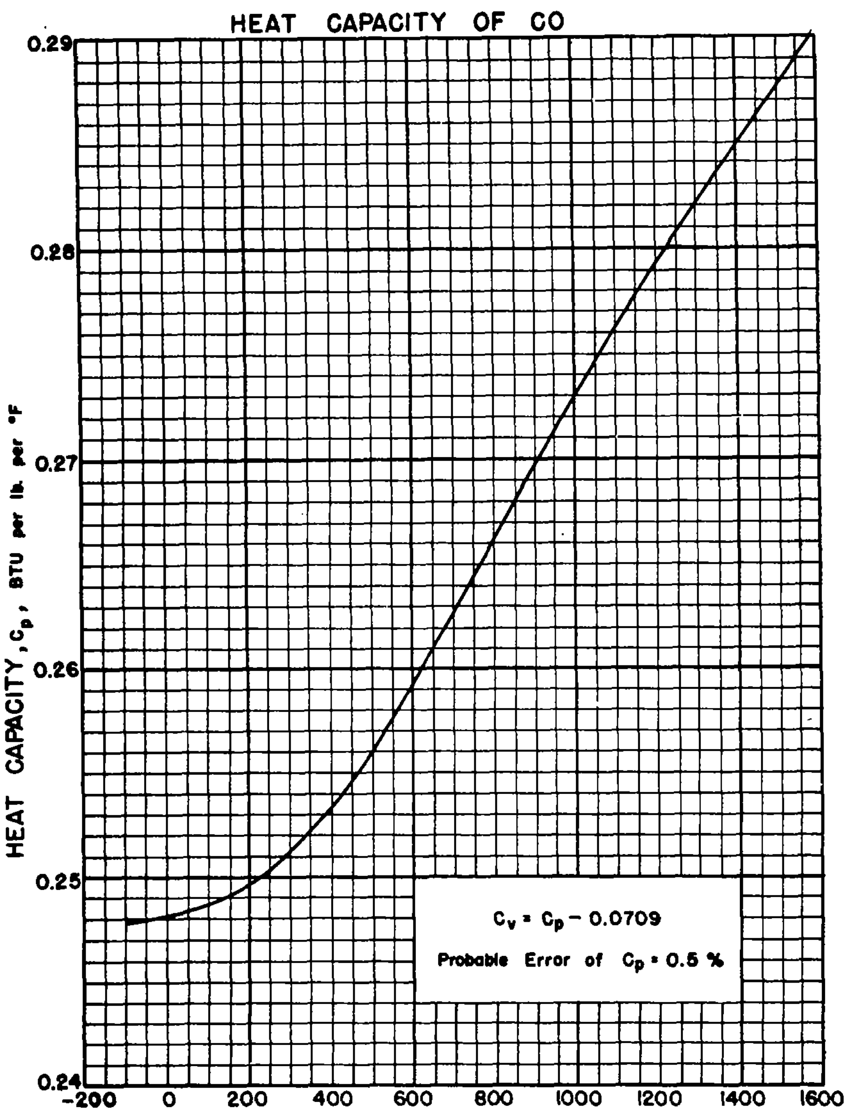
HEAT CAPACITY OF CO
HEAT CAPACITY, C_p, BTU per lb. per °F
TEMPERATURE, °F
$C_v = C_p - 0.0709$
Probable Error of C_p = 0.5 %
0.29
0.28
0.27
0.26
0.25
0.24
-200
0
200
400
600
800
1000
1200
1400
1600

FIG. 23

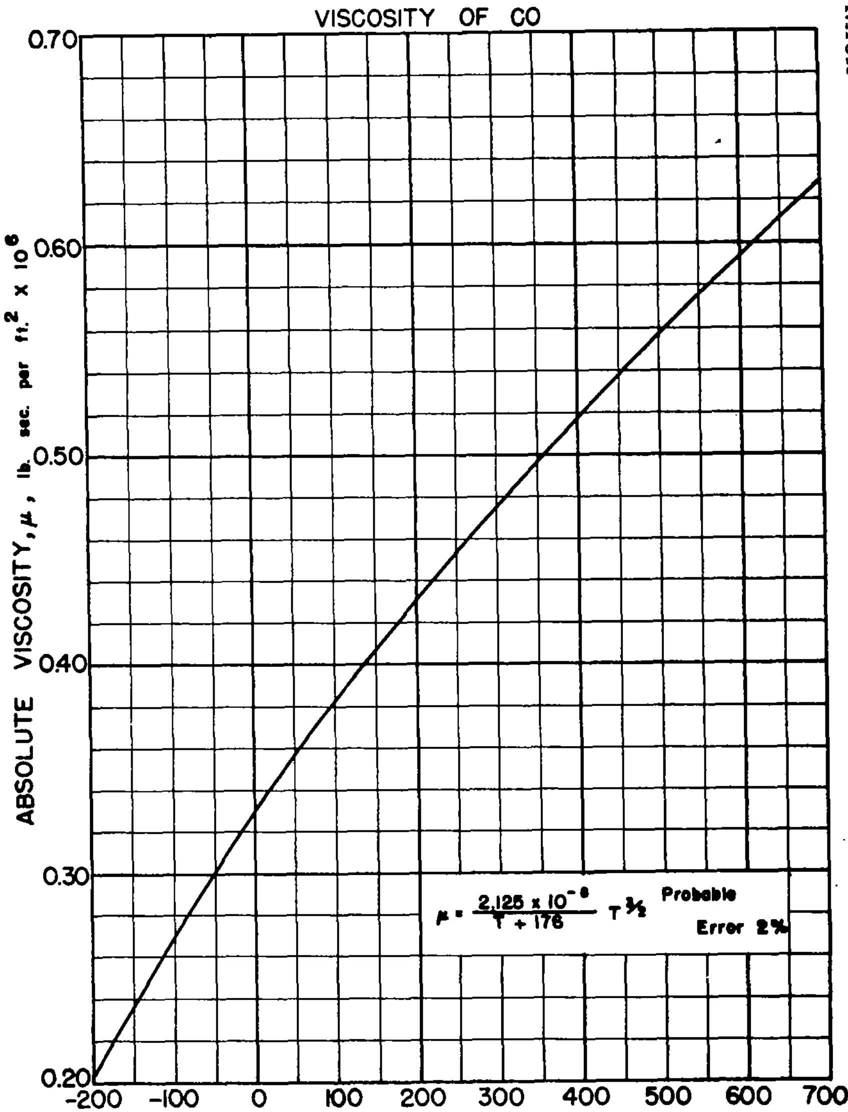
VISCOSITY OF CO
ABSOLUTE VISCOSITY, μ, lb. sec. per ft.^{2} x 10^6
TEMPERATURE, °F
$\mu = \frac{2.125 \times 10^{-8}}{T + 176} T^{3/2}$
Probable Error 2%
0.70
0.60
0.50
0.40
0.30
0.20
-200
-100
0
100
200
300
400
500
600
700

FIG. 24

VISCOSITY OF CO

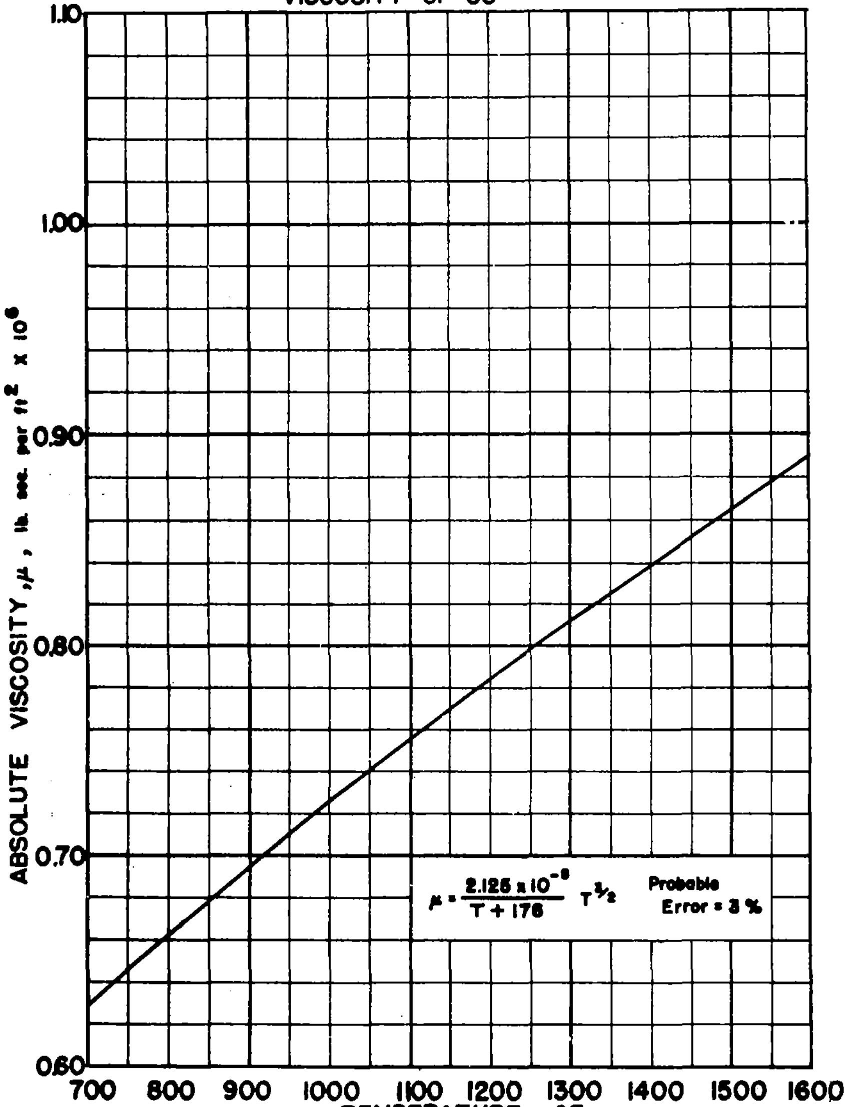

FIG. 25

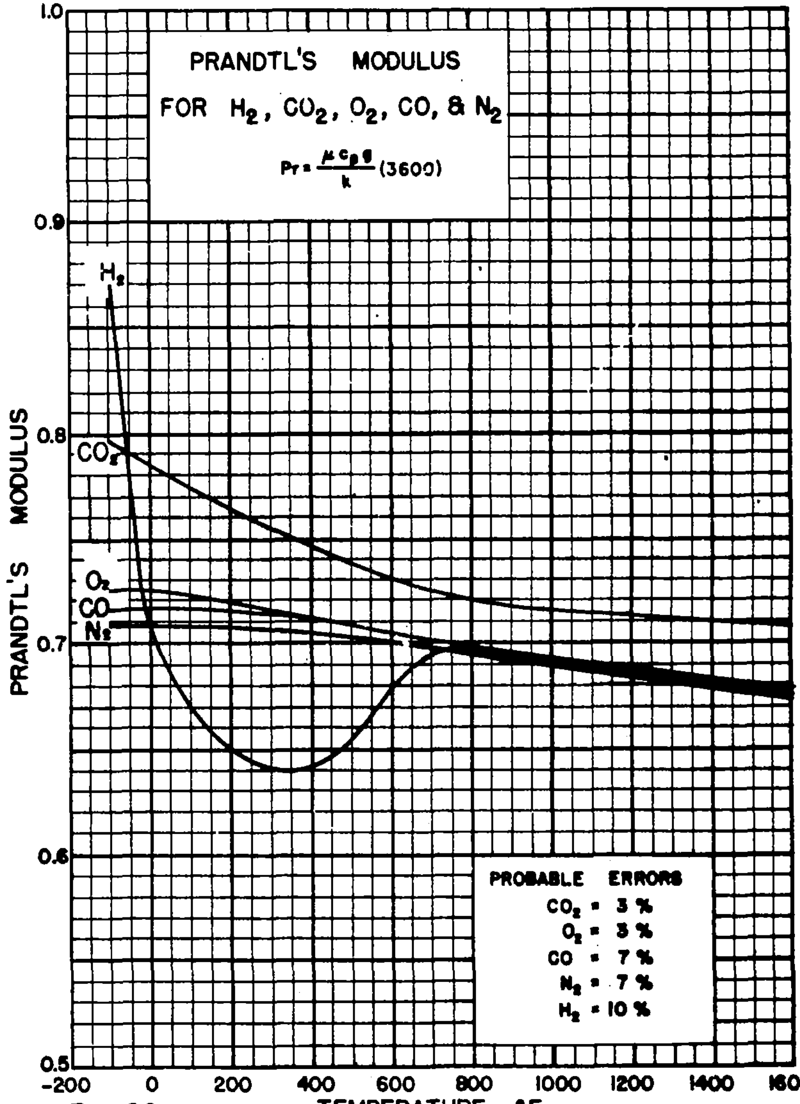

FIG. 26

THERMAL CONDUCTIVITY OF CO

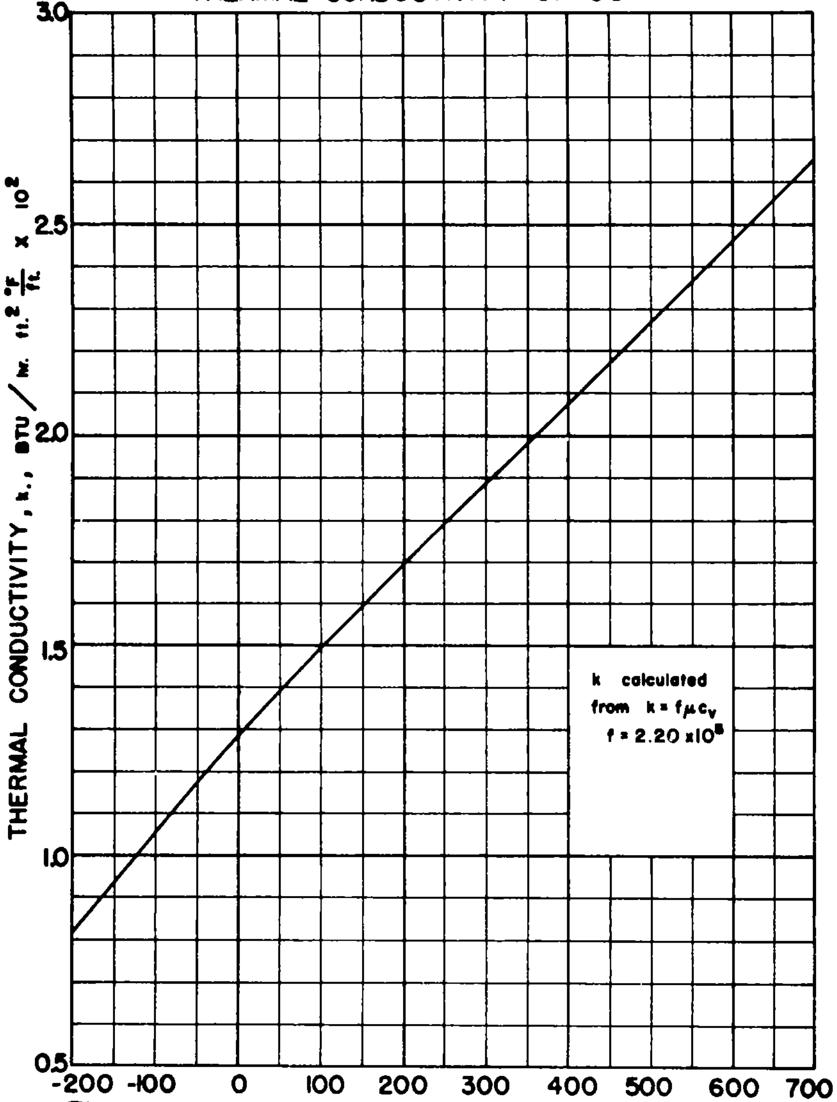

FIG. 27

THERMAL CONDUCTIVITY OF CO

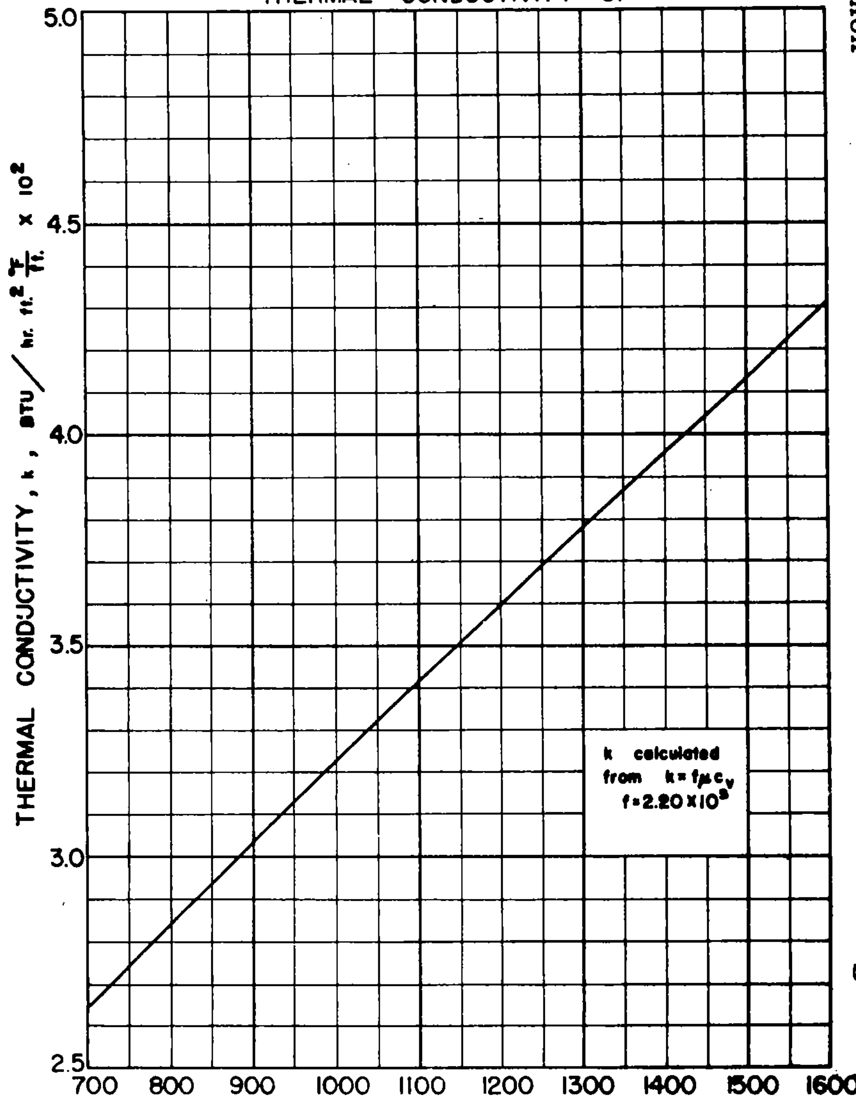

FIG. 28